SIELETERS: a Static Fourier Transform Infrared Imaging Spectrometer for Airborne Hyperspectral Measurements

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1. Introduction

An airborne hyperspectral imaging system named SYSIPHE is currently being developed by ONERA, France, under the contracting authority of the French MoD. This system will be dedicated to making absolute measurements of spectral radiances and emissivities of various ground scenes, in order to create an important ground hyperspectral data base. All the data collected will in turn be used in several defense applications.

The measurement part of SYSIPHE will be composed of two optical instruments, together integrated into a DO-228 plane held by the German DLR. One of the instruments is working in the visible, near infrared and short wave infrared (SWIR) domains. It is named HySpex2 and is being developed by NEO and FFI, Norway. SIELETERS, being developed by ONERA, is the second one and is working in the medium wave infrared (MWIR) and long wave infrared (LWIR) domains. SIELETERS and HySpex2 will be integrated simultaneously above the plane hatch.

This paper describes the instrumental concept (Section 2) and the main parts design of SIELETERS (Sections 3 and 4), as well as its estimated performances (Section 5).

2. SIELETERS instrumental concept

The instrument concept is derived from technical requirements which are summarized in Table 1 below :

Parameter	Specifications	Comments
Spectral range	870-1250 cm^{-1} and 2000-3333 cm^{-1}	i.e. 8-11,5 µm (LWIR) and 3-5 µm (MWIR) ranges.
Spectral resolution	< 24 cm^{-1}	
Ground sampling distance	0,5m	Size of the ground sample for a flight at 2000m above ground.
Field of view	± 7° (across track)	Swath of 500 m at 2000 m above ground
Typical temperature range of observed scenes	0°C < T_{scene} < 100°C	

Table 1. Main technical requirements for SIELETERS

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14. ABSTRACT

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To meet those requirements, it has been chosen to build SIELETERS from two separated optical modules, both mounted on the same stabilization platform. One module is dedicated to the MWIR domain and the other one to the LWIR domain.
Each optical module is an imaging spectrometer, made of a static Fourier Transform Spectrometer (FTS) associated with imaging optics. Instantaneously, a portion of ground scene observed is imaged onto the focal plane arrays, each pixel of the image (in the direction of the flight) "seen" through a different value of the optical path difference (OPD), as it is explained in details in Section 3. The whole image of the scene and the total interferogram of each ground sample are then obtained by the carrier linear motion over the scene. The spectral information of each point in the scene is to be retrieved by numerical treatment over the interferograms acquired.
The stabilization platform is needed to make the optical modules stay in the Nadir line of sight very precisely during the duration of the flight measurement phase. Its design is described in Section 4.

Figure 1 below shows three-dimensionnal views of the optical modules mounted in the stabilization platform over the plane's hatch. On the picture are also represented the electronic modules that digitize and transfer the detectors data to the control rack for real-time quick-look and storage.

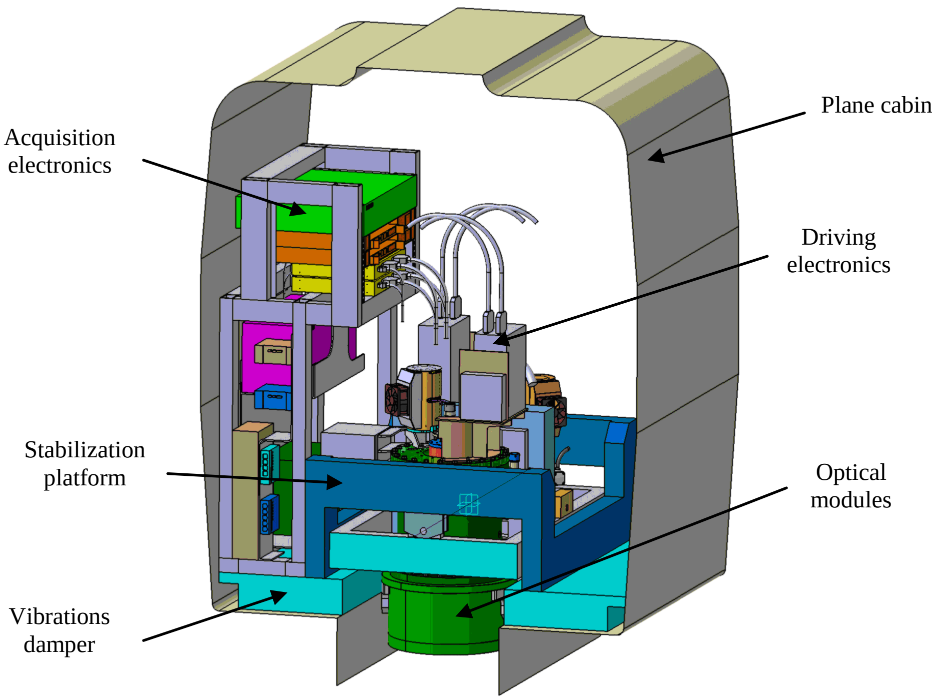

Figure 1. Optical modules and stabilization platform over the plane's hatch

The MWIR and LWIR optical modules weigh around 50kg, and have a cylindrical shape.

3. Optics and detector design

Both MWIR and LWIR modules share the same optical architecture, represented schematically on Figure 2 below. The two main parts are the interferometer and the following imaging optics. The light coming from the ground scene first enters into the instruments through a wide-band window, that closes the cryostat in which the optics are integrated and protects them from outside pollution. The bending mirror rotates the rays of 90° in order to make them be incident on the beamsplitter inside the interferometer with an angle of 45°. The light then follows its path through the interferometer, propagates into the imaging optics and is finally focused on the optics focal plane.

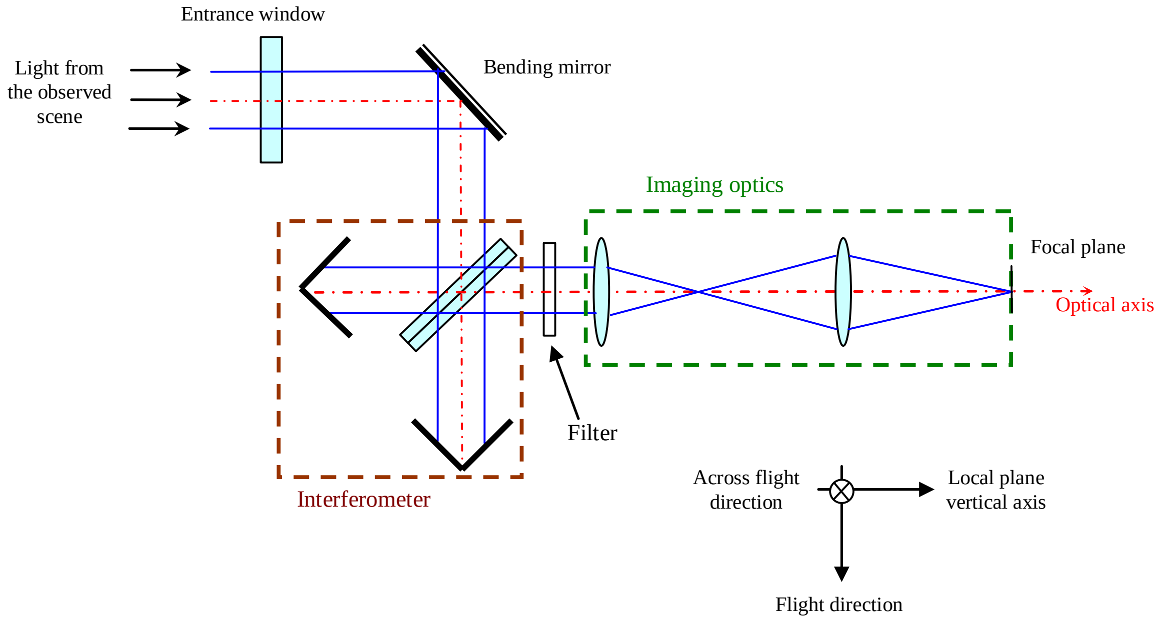

Figure 2. Optical architecture of the MWIR and LWIR imaging spectrometers

The optical concept of both LWIR and MWIR modules is based on a static “grande étendue” FTS built on a Michelson interferometer where mirrors are replaced by dihedrons[1],[2]. The interferometer principle is shown in Figure 3. One of the dihedron is slightly shifted perpendicularly to the optical axis in order to create a lateral shift between the two interfering out-going rays, coming from the same entering ray (collimated light enters the interferometer) and being separated by the beamsplitter. The lateral shift produces in turn a fixed linear variation of the optical path difference, function of the entering ray angle of incidence in the flight direction. This fixed linear fringes system produced by the interferometer is then imaged at the focal plane of suitable imaging optics, as well as the observed scene, which is modulated by the variation of the OPD in the flight direction. This means that each point of the “interfero-image” acquired is the image of the corresponding point in the observed scene but modulated through the value of the OPD at the point position in the flight direction. It is then necessary to make each ground scene point pass over every value of the OPD to acquire the entire interferogram of its spectral signature. This is obtained thanks to the linear motion in the flight direction of the airborne instruments over the observed scene.

The OPD evolution with the field of view in the flight direction (named “along track” or ALT, direction) is given by the following expression :

$$\delta(\theta_{ALT}) = -t \times \sin(\theta_{ALT}) + \delta_0$$

Where t is the constant lateral shift between out-going rays (from the same incident rays), θ_{ALT} is the field of view angle in the along track direction and δ_0 is an offset which depends on the relative position of the dihedrons.

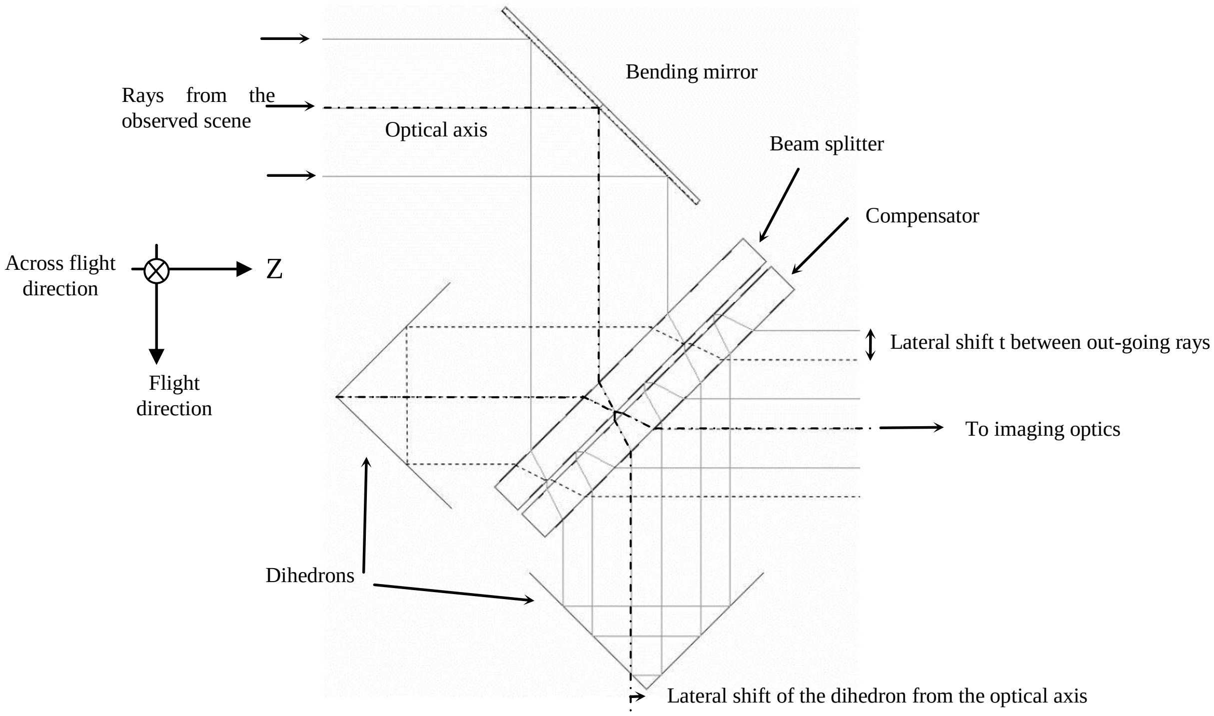

Figure 3. Interferometer principle

The imaging optics is entirely made of lenses, mounted in a tubular mechanical structure. A filter is integrated between the interferometer and the imaging optics in order to define precisely the spectral range of each module.

In both MWIR and LWIR modules, all the optical components are integrated inside a cryostat, in a vacuum and cryogenic environment (temperature around 100K). This is necessary to optimize the radiometric performances the instruments, by reducing strongly the instruments’ undesirable self-emission radiation. Pressure and temperature sensors are integrated at various locations inside the MWIR and LWIR cryostats in order to verify at each moment that the optics stay in the required environmental conditions.
The MWIR module layout is shown in Figure 4 below, the LWIR module has a very similar optical and mechanical architecture.

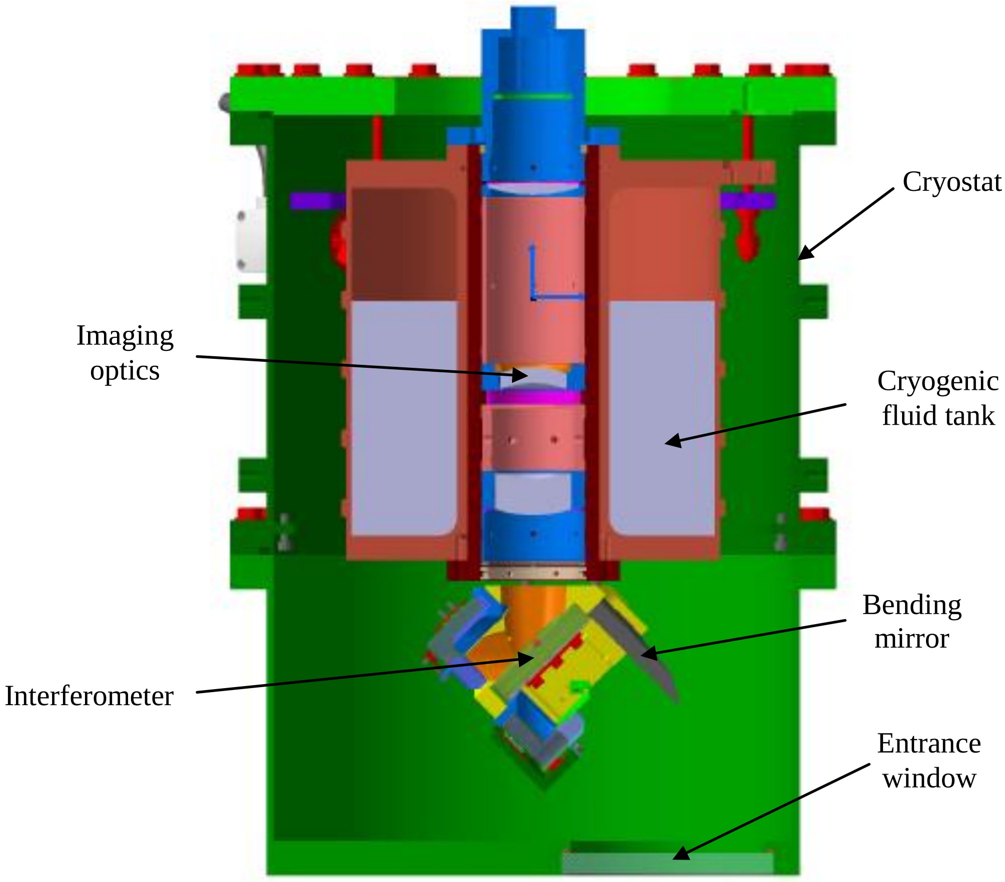

Figure 4. MWIR module’s opto-mechanical layout

For the detection of the “interfero-image” formed at the imaging optics focal plane in both LWIR and MWIR modules, innovative large-format infrared focal plane arrays (IRFPAs) were specifically developed by Sofradir in order to optimize the instrument performances. Both LWIR and MWIR IRFPAs have 1000×400 pixels to cover 500m across track with the required 0,5m ground sampling pitch.

The MWIR and LWIR detectors are embedded in a specific cryostat and cooled at a temperature under 77K by a Stirling cryocooler, as represented on the following Figure 5 :

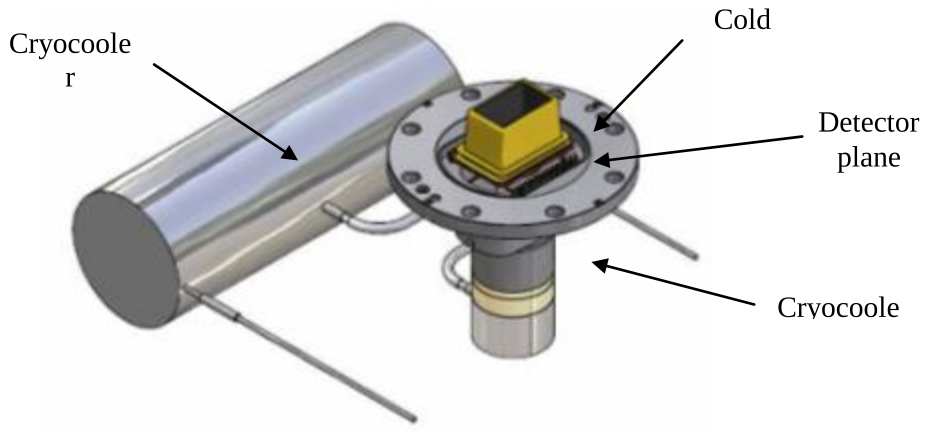

Figure 5. Detector cryostat and cryocooler

The read-out frequency of the detectors is adapted to the ground speed of the plane above the scene. This implies a very high data rate to deal with. Therefore, specific electronic devices have been developed to drive the IRPFAs and to digitize the high rate and high dynamic data they produce. The amount of data is then transferred into storage units using suitable high rate data link.

4. Stabilization platform design

The stabilization platform is based on a gimbaled structure. It is composed of three interlocked frames, one for each rotation along the yaw, pitch and roll axis. The external frame is fixed to the floor by means of a shock absorber. This is to filter the vibrations of the aircraft. The first inside frame adjust the roll angle on the reference frame. The second frame treats the pitch angle. And the last frame has two functions : to adjust yaw angle and to support the two opticals modules of SIELETERS. This design is presented on the following Figure 6 :

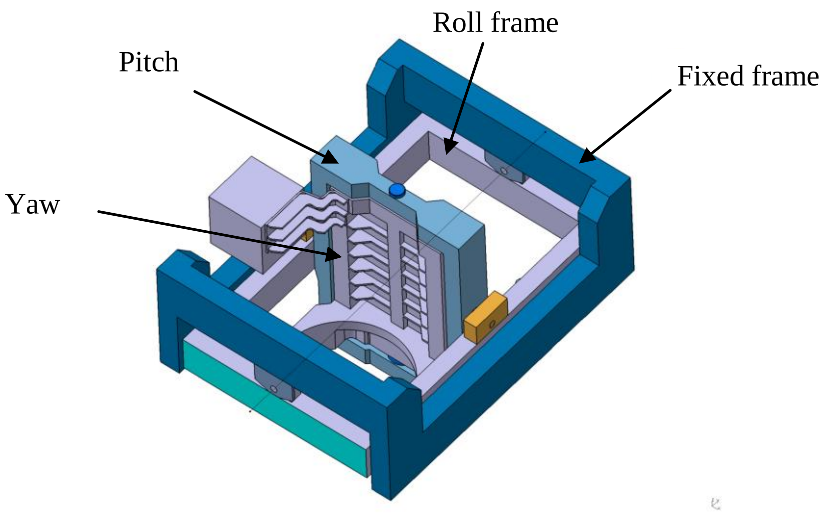

Figure 6. Stabilization platform mechanical design

The rotation motions are driven by a control unit (DSP board) associated with sensors and actuators. The whole system therefore stabilizes the imaging spectrometers lines of sight in order to make them stay in the Nadir direction during the measurement phase of the flight. The optical lines of sight stay in the Nadir direction with a precision better than 100µrad.

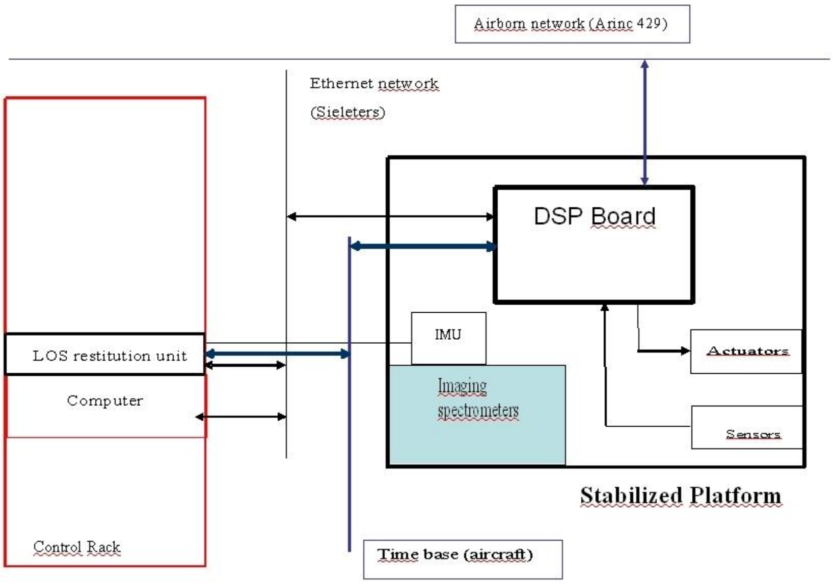

Figure 7. Principle of the stabilization platform's control system

The control unit (DSP board embedded on the stabilization platform) calculates the corrections to bring to the rotation motions from the platform attitude information (sensors) provided by the module that retrieves the line of sight direction at each acquisition time of the IRFPAs. The main part of these sensors is composed of gyrometers and axial-encoders. The control unit is also connected with the airborne network to get the aircraft attitude information and the base time to synchronize the data.

For geometry and hyperspectral treatments, an Inertial Motion Unit (IMU), fixed "strapdown" onto the instrument, is used to provide attitude measurements. Those measurements are then acquired by a specific control unit manufactured by Applanix (LOS restitution unit in the above Figure 7). This unit is also linked to a DGPS system. The antenna is installed on the top of the aircraft. This system determines the absolute position of the lines of sight at each acquisition time.

These information are instantaneously transmitted to the stabilization platform control system, so as to ensure the Nadir line of sight. All the line of sight attitude data are stored during the flight. After the flight, it will be injected into the data processing chain that will be performed on the raw "interfero-image" data acquired by the imaging spectrometers, in order to retrieve both spectral and radiometric information of each pixel in the ground scene observed.

5. Expected performances

A model of radiometric performances for both MWIR and LWIR modules has been developed in order to estimate and optimize the instruments performances during the design phase of SIELETERS.
This model requires input data parameters representative of the ground scene observed, the optical architecture, and the IRFPA characteristics. It produces estimated radiometric performances like signal to noise ratios on the acquired interferogram and on the radiance spectrum derived from the interferogram.

Following Table 2 gives some radiometric performances values for different cases of scene's temperature (black-body material for all ground pixels), for two different wavelengths in the MWIR domain and LWIR domains :

Scene temperature	**Noise equivalent temperature difference (NETD)**
300 K	< 150 mK @ 5µm < 200 mK @ 10µm
333 K	< 250 mK @ 5µm < 250 mK @ 10µm

Table 2. Radiometric performances of SIELETERS

6. Conclusion and acknowledgments

The design phase has been completed and SIELETERS is now in its realization phase.

The SIELETERS team acknowledges the work of the Institut d'Optique *Graduate School* in the opto-mechanical design of the imaging spectrometers and of Sofradir in the development and realization of the IRFPAs.
It also thanks the French MoD for its decisive technical and financial involvement.

7. References

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